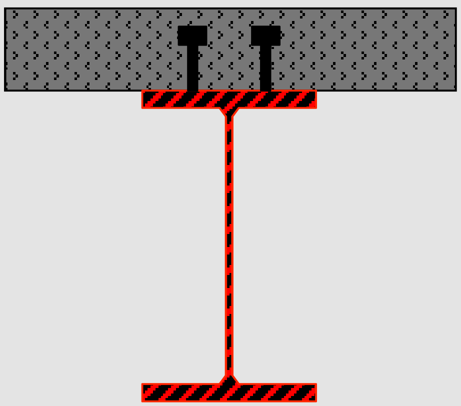
C & EE 141

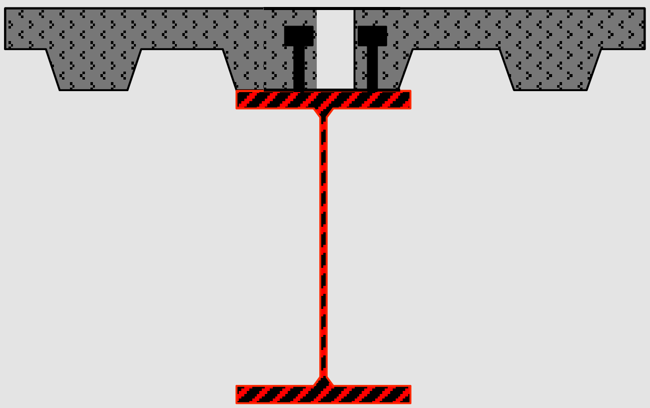
Composite Beam Design
Part 1

What is a composite beam?

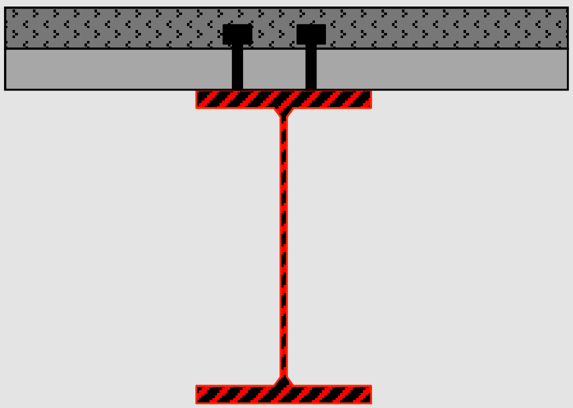
- A composite beam is a beam that utilizes a combination of a steel beam and a concrete slab to form a combined section to resist loading.



Concrete Flat Slab

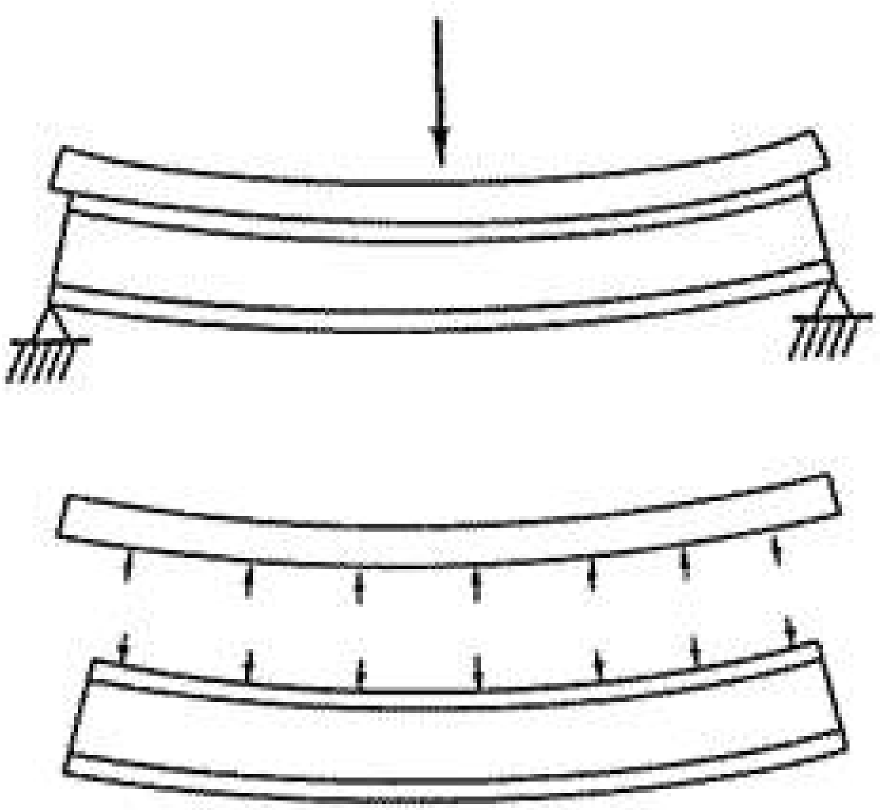


Concrete Fill on Metal Deck (Parallel to Flute)



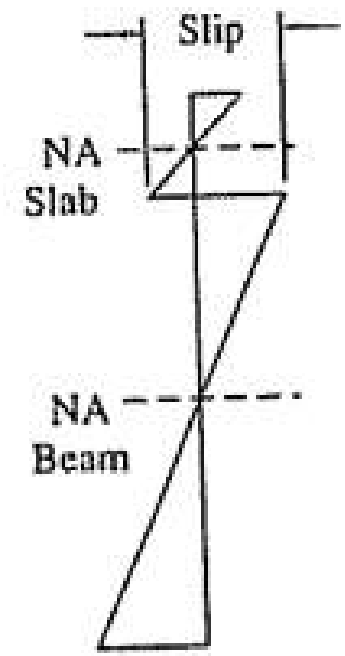
Concrete Fill on Metal Deck (Perpendicular to Flute)

Non-Composite Beam Behavior



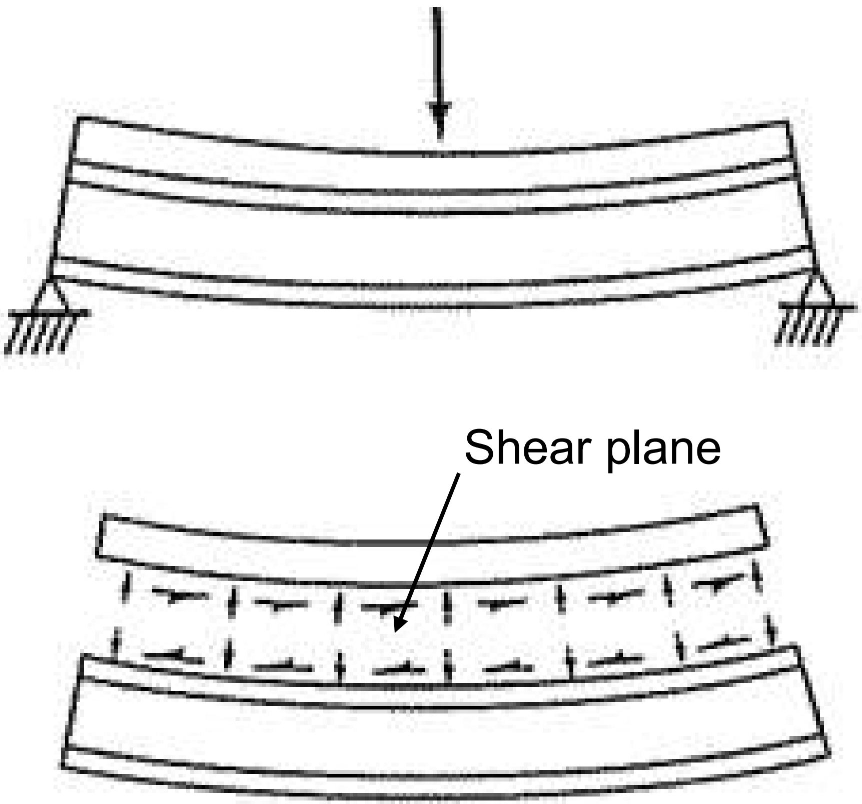
No Interaction Between Concrete & Steel

Separate Moments in Slab & Beam

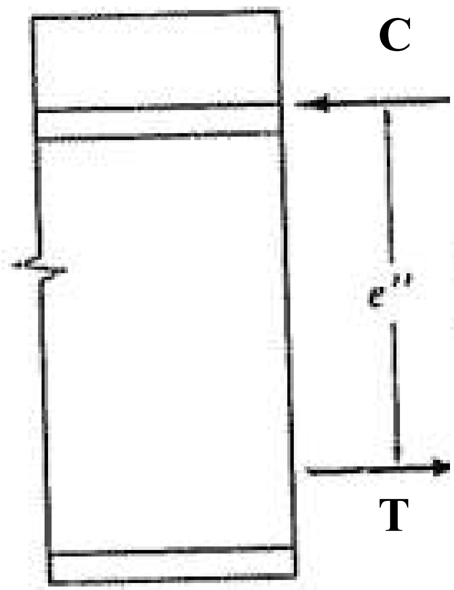


Independent Stress-Strain Diagrams

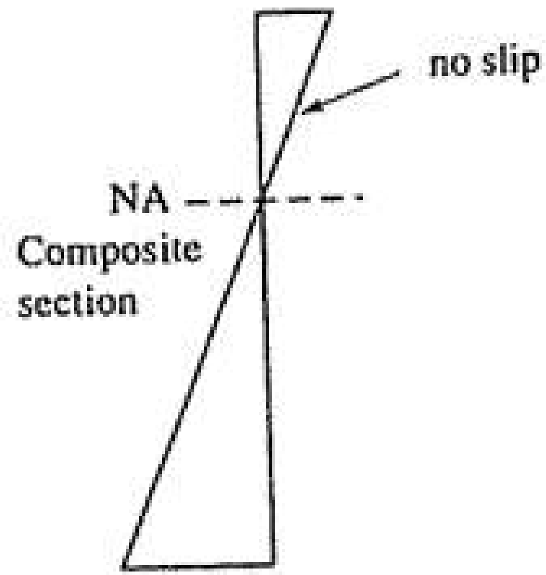
Composite Beam Behavior



Interaction Between Concrete & Steel

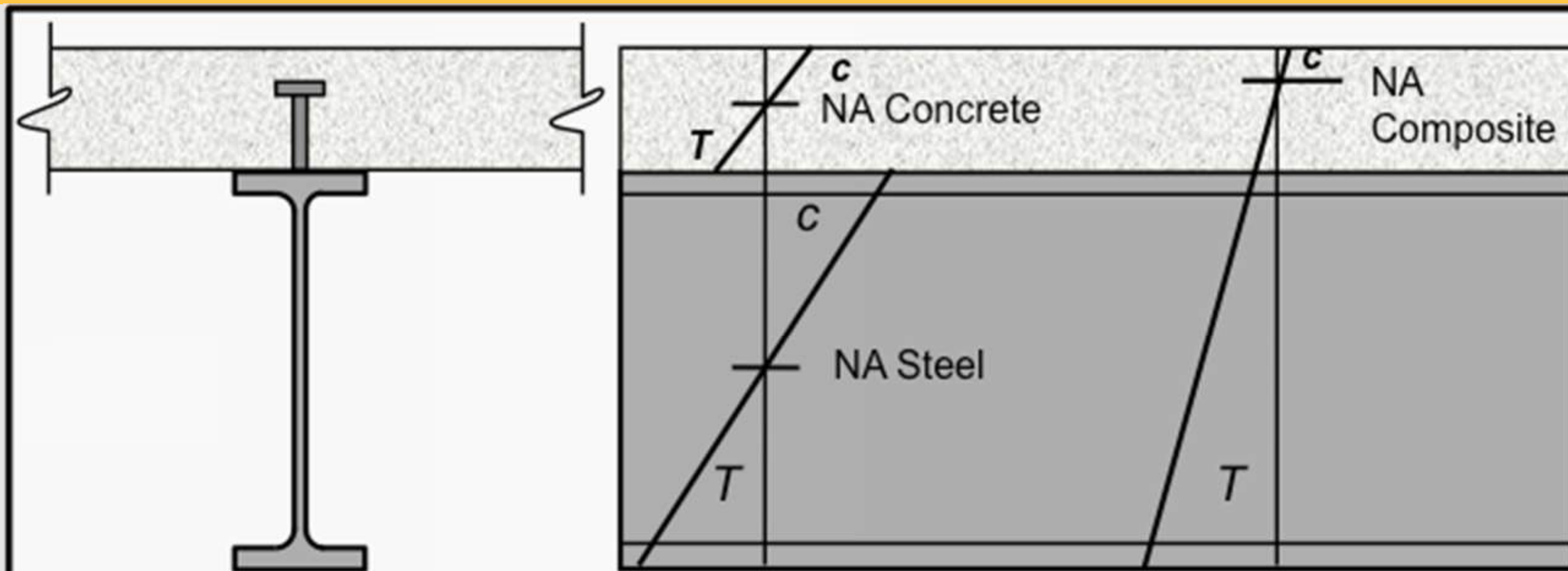


Moment Resolved into T/C Couple



One Related Stress-Strain Diagram

Composite Beam Behavior



Non-Composite

- Slip at Interface
- Two Neutral Axes
- $M_n = M_{nconcrete} + M_{nsteel}$
- $I = I_{concrete} + I_{steel}$

Fully Composite

- Assumed no slip at Interface
- One Neutral Axes
- $M_n >> M_{nconcrete} + M_{nsteel}$
- $I >> I_{concrete} + I_{steel}$
- Shear at interface transferred by shear connectors.

Why use a composite beam?

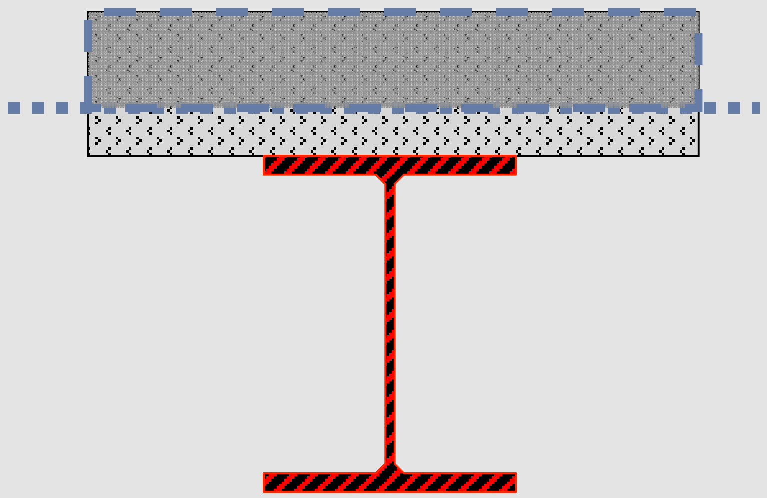
- Reduction in the weight of steel
- Shallower steel beams
- Increased floor stiffness
- Increased span length for a given member
- Better utilization of materials
  - A wearing surface (concrete slab) is typically required anyway
  - Using the concrete in compression and steel in tension

Assumptions for Composite Design

- Ultimate strength is based on plastic behavior
  - Concrete reaches ultimate compressive stress of 0.85 f'c
  - Steel beam yields in tension, top may yield in compression
- PNA may fall within slab or beam.
  - Finding PNA is key to calculating capacity.

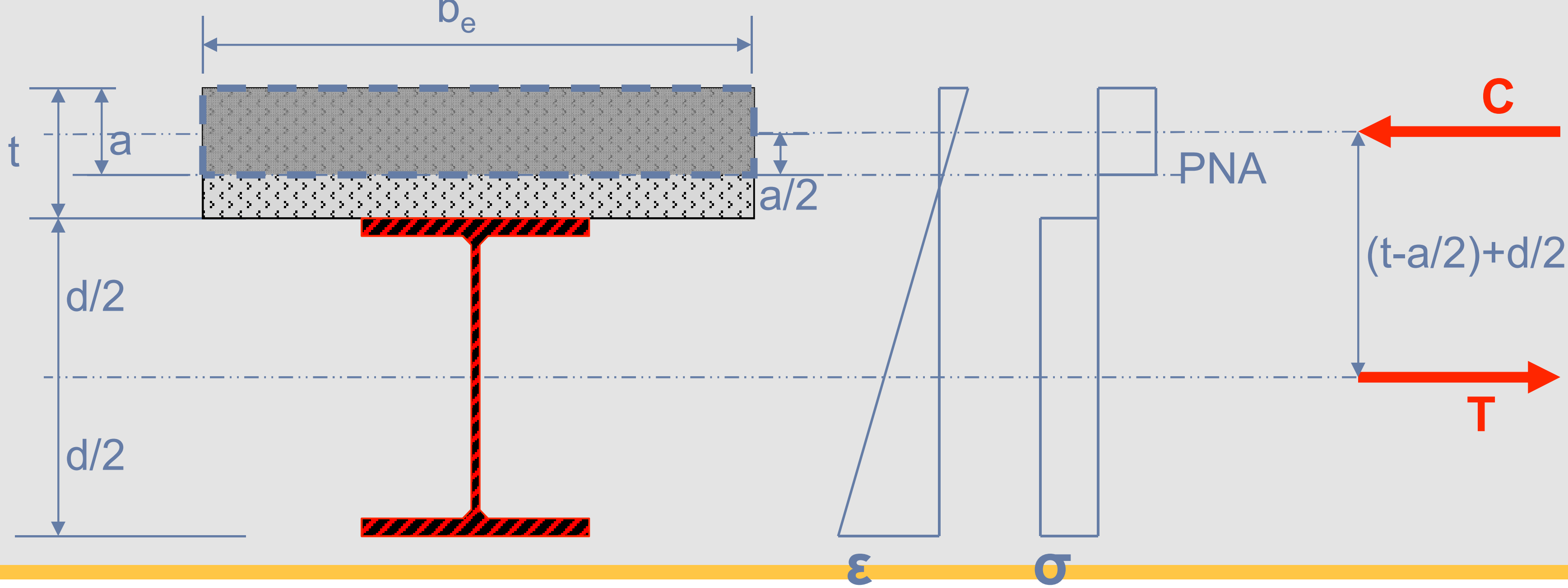
Plastic Neutral Axis (PNA) in the Concrete

- If PNA is in the concrete, the entire steel section is yielded in tension.
- Most common case.



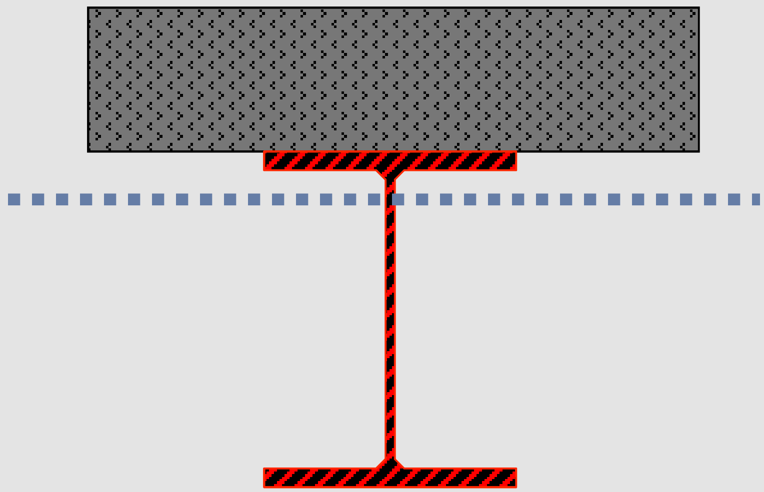
Flexural Strength
PNA in Slab

- **T=C=**A_sF_y=0.85f'_c a b_e
- $\mathbf{M_n}$=A_sF_y(t-a/2+d/2)   [summing moments about top of steel]
- Shear at concrete/steel interface, V' = 0.85$f'_c a b_e$



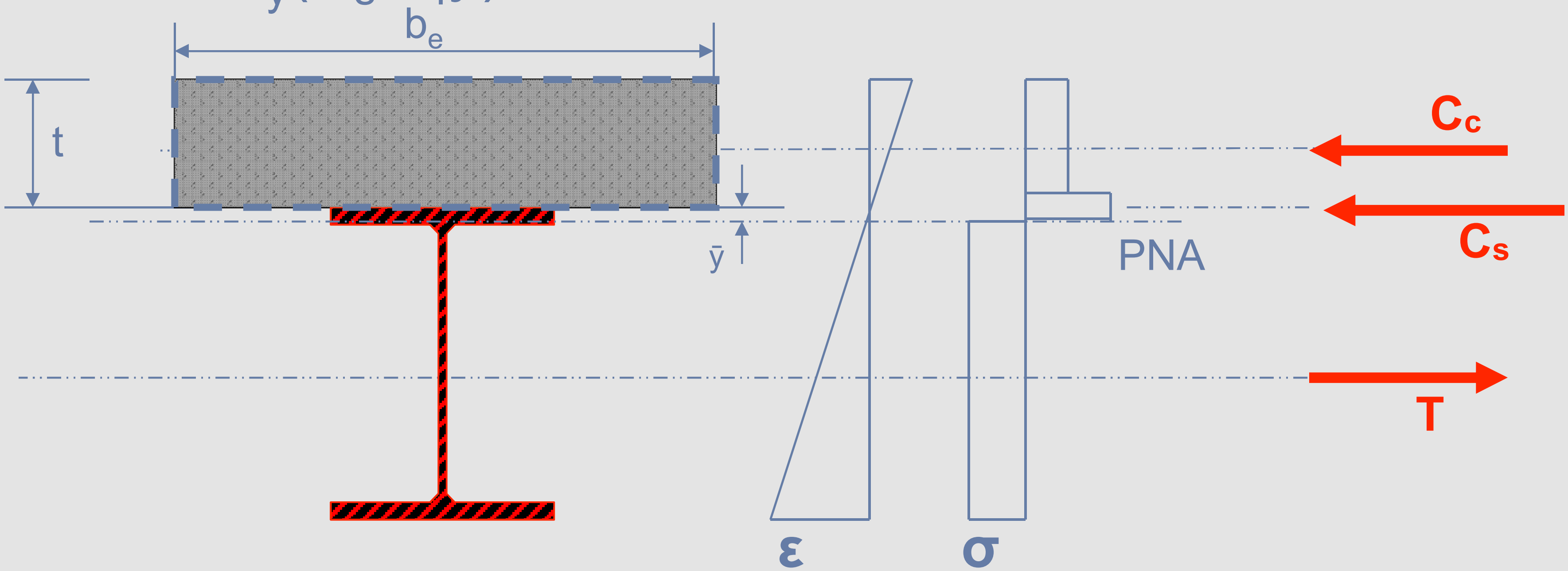
Plastic Neutral Axis (PNA) in the Steel Beam

- If PNA is in the steel, the entire concrete section has reached the maximum compressive strength.
- Compression is needed in the top portion of steel beam to equal tension in balance of beam.
- The shear across the interface, $V = 0.85f'_c A_c$



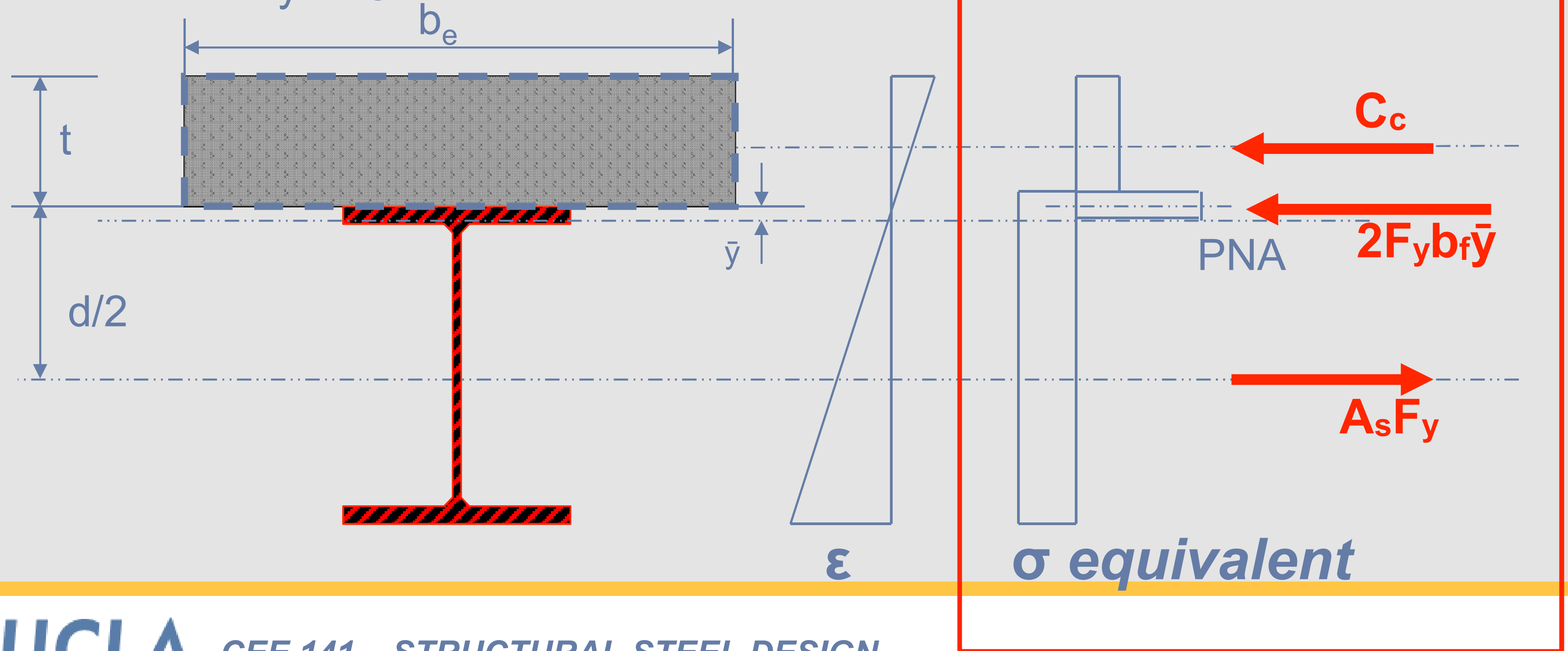
Static Equilibrium
PNA in Top Flange

- $Cc = 0.85f'_c b_e t$
- $Cs = F_y b_f \bar{y}$
- $T = F_y(A_s - b_f \bar{y})$



Flexural Strength
PNA in Top Flange

- $Cc = 0.85f'_c b_e t$
- $Cs = F_y b_f \bar{y}$
- $T = F_y(A_s - b_f \bar{y})$



Flexural Strength
PNA in Top Flange

$$C_c + C_s = T$$

$$0.85f'_c b_e t + F_y b_f \bar{y} = F_y A_s - F_y b_f \bar{y}$$

$$\bar{y} = \frac{F_y A_s - 0.85f'_c b_e t}{2F_y b_f}$$

$$M_n = 0.85f'_c b_e t\left(\frac{t}{2}\right) + F_y A_s\left(\frac{d}{2}\right) - 2F_y b_f \bar{y}\left(\frac{\bar{y}}{2}\right)$$

- Summing moments about top of steel
- Shear at concrete/steel interface, $V' = 0.85f'_c a b_e$

Flexural Strength

2a. Positive Flexural Strength

The *design positive flexural strength*, $\phi_b M_n$, and *allowable positive flexural strength*, M_n/Ω_b, shall be determined for the *limit state* of *yielding* as follows:

$$\phi_b = 0.90 \text{ (LRFD)} \qquad \Omega_b = 1.67 \text{ (ASD)}$$

(a) When $h/t_w \le 3.76\sqrt{E/F_y}$

M_n shall be determined from the plastic *stress* distribution on the composite section for the limit state of *yielding (plastic moment)*.

> **User Note:** All current ASTM A6 W, S and HP shapes satisfy the limit given in Section I3.2a(a) for $F_y \le 50$ ksi (345 MPa).

(b) When $h/t_w > 3.76\sqrt{E/F_y}$

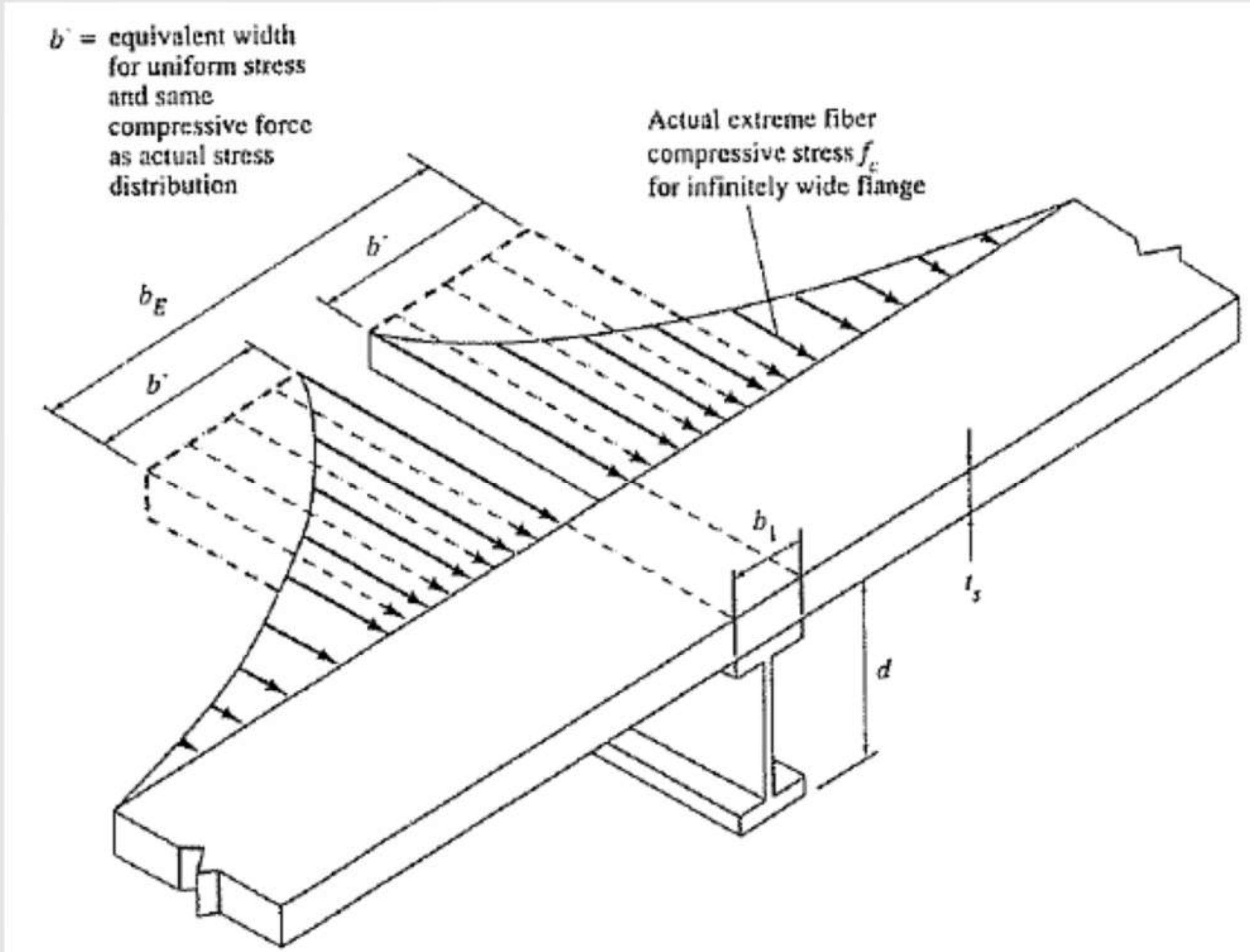
M_n shall be determined from the superposition of elastic stresses, considering the effects of shoring, for the limit state of *yielding (yield moment)*.

Spec I3.2a

EXAMPLE PROBLEMS

Effective Width in Concrete

- Because the stress distribution is not uniform, a simplification of the width of concrete slab that is effective for flexure is used.

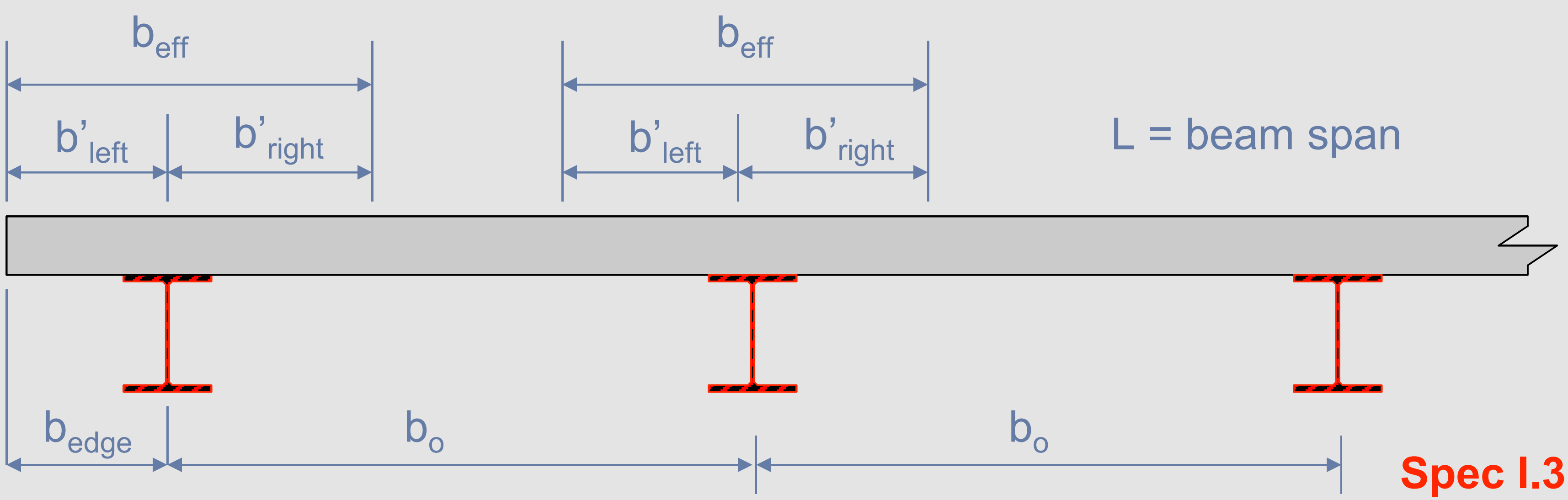


Effective Width

1a. Effective Width

The *effective width* of the concrete slab shall be the sum of the effective widths for each side of the *beam* centerline, each of which shall not exceed:

(1) one-eighth of the beam span, center-to-center of supports; **$b' = L/8$**
(2) one-half the distance to the centerline of the adjacent beam; or **$b' = b_o/2$**
(3) the distance to the edge of the slab. **$b' = b_{edge}$**



Spec I.3

Shear Connectors: Headed Studs

- Means of connecting concrete and steel beam to act together
- Headed Studs which are similar to a steel bolt are typically used
- Base of stud is welded to top flange of steel beam through the metal deck
- Come in various lengths and diameters ($L > 4\ \Phi_{stud}$)

Shear Stud Capacity

2a. Strength of Steel Headed Stud Anchors

The *nominal shear strength* of one steel headed stud anchor embedded in a solid concrete slab or in a composite slab with decking shall be determined as follows:

$$Q_n = 0.5 A_{sa} \sqrt{f_c' E_c} \le R_g R_p A_{sa} F_u \quad \text{(I8-1)}$$

where

A_{sa} = cross-sectional area of steel headed stud anchor, in.^{2} (mm^2)

E_c = modulus of elasticity of concrete

$= w_c^{1.5}\sqrt{f_c'}$, ksi $\left(0.043 w_c^{1.5}\sqrt{f_c'}\text{, MPa}\right)$

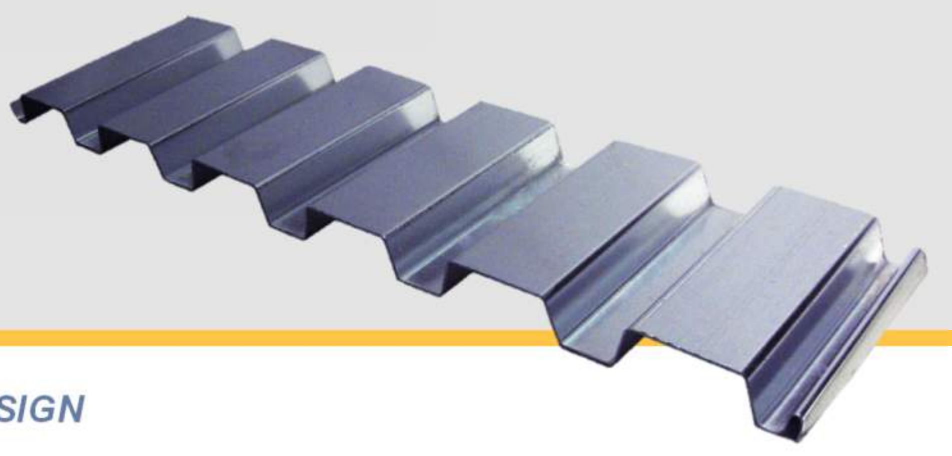
F_u = *specified minimum tensile strength* of a steel headed stud anchor, ksi (MPa)

R_g & R_p are coefficients related to the geometry of the slab/steel deck, number of studs per deck rib and the position of the stud within the rib

Spec I.8

Metal Deck

- Typical slab construction in steel framed buildings.
- Behaves as one-way slab with deck providing tension reinforcement.
- Corrugated gage plate (i.e. 20 gage)
- Various deck depths (i.e. 3”)
- Various concrete fill depths (i.e. 6¼”) – typically thickness a function of fire rating

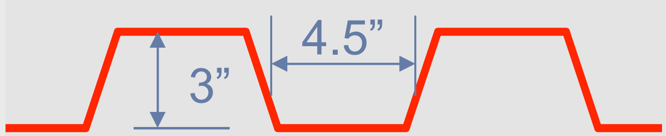


User Note: The table below presents values for R_g and R_p for several cases. Capacities for steel headed stud anchors can be found in the Manual.

Condition	R_g	R_p
No decking	1.0	0.75
Decking oriented parallel to the steel shape		
$\frac{w_r}{h_r} \geq 1.5$	1.0	0.75
$\frac{w_r}{h_r} < 1.5$	0.85^{**}	0.75
Decking oriented perpendicular to the steel shape Number of steel headed stud anchors occupying the same decking rib		
1	1.0	0.6^{+}
2	0.85	0.6^{+}
3 or more	0.7	0.6^{+}

h_r = nominal rib height, in. (mm)
w_r = average width of concrete rib or haunch (as defined in Section I3.2c), in. (mm)
** for a single steel headed stud anchor
$^{+}$ this value may be increased to 0.75 when $e_{mid\text{-}ht} \geq 2$ in. (51 mm)

Typical Floor Deck Profile



i.e. for studs in “strong” position

Spec I.8

Shear Stud Capacity

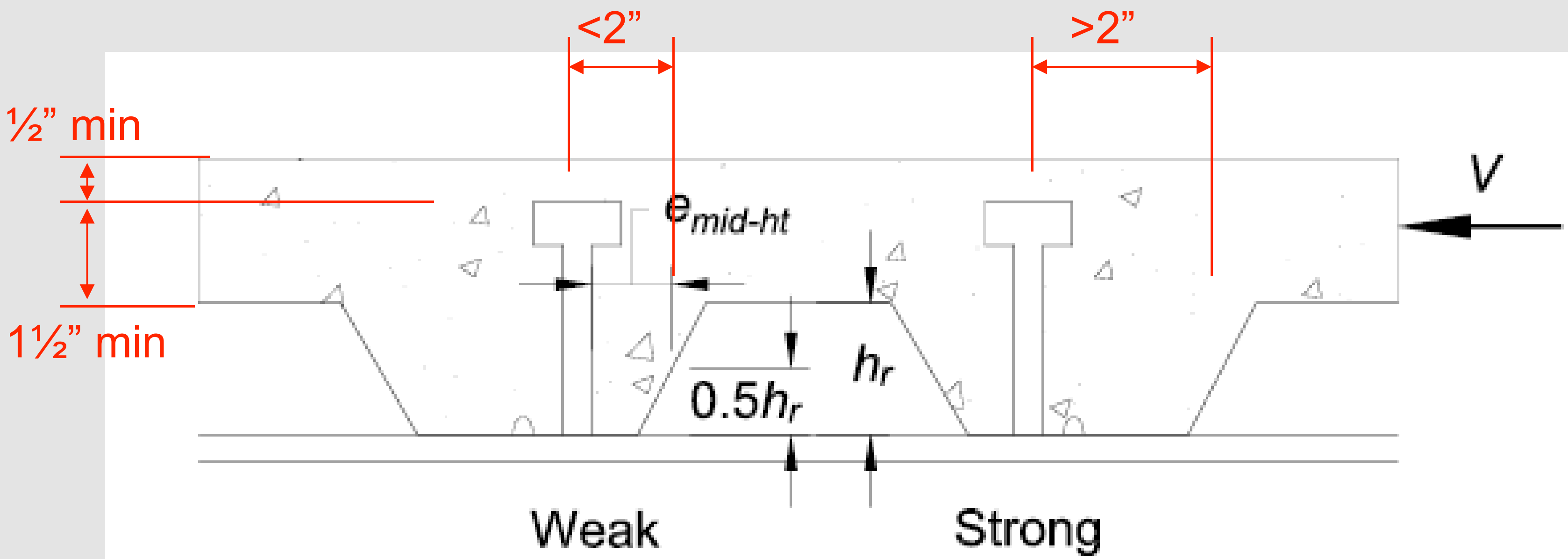


Fig. C-I8.1. Weak and strong stud positions [Roddenberry et al. (2002b)].

Table 3-21
Shear Stud Anchor

F_u = 65 ksi

Q_n

Nominal Horizontal Shear Strength for One Steel Headed Stud Anchor, Q_n, kips

Deck condition			Stud anchor diameter, in.	Normal weight concrete w_c = 145 pcf, f'_c = 3 ksi	Normal weight concrete w_c = 145 pcf, f'_c = 4 ksi	Lightweight concrete w_c = 110 pcf, f'_c = 3 ksi	Lightweight concrete w_c = 110 pcf, f'_c = 4 ksi
No deck			3/8	5.26	5.38	4.28	5.31
			1/2	9.35	9.57	7.60	9.43
			5/8	14.6	15.0	11.9	14.7
			3/4	21.0	21.5	17.1	21.2
Deck Parallel	$\frac{w_r}{h_r} \geq 1.5$		3/8	5.26	5.38	4.28	5.31
			1/2	9.35	9.57	7.60	9.43
			5/8	14.6	15.0	11.9	14.7
			3/4	21.0	21.5	17.1	21.2
	$\frac{w_r}{h_r} < 1.5$		3/8	4.58	4.58	4.28	4.58
			1/2	8.14	8.14	7.60	8.14
			5/8	12.7	12.7	11.9	12.7
			3/4	18.3	18.3	17.1	18.3
Deck Perpendicular	Weak studs per rib (R_p = 0.60)	1	3/8	4.31	4.31	4.28	4.31
			1/2	7.66	7.66	7.60	7.66
			5/8	12.0	12.0	11.9	12.0
			3/4	17.2	17.2	17.1	17.2
		2	3/8	3.66	3.66	3.66	3.66
			1/2	6.51	6.51	6.51	6.51
			5/8	10.2	10.2	10.2	10.2
			3/4	14.6	14.6	14.6	14.6
		3	3/8	3.02	3.02	3.02	3.02
			1/2	5.36	5.36	5.36	5.36
			5/8	8.38	8.38	8.38	8.38
			3/4	12.1	12.1	12.1	12.1
	Strong studs per rib (R_p = 0.75)	1	3/8	5.26	5.38	4.28	5.31
			1/2	9.35	9.57	7.60	9.43
			5/8	14.6	15.0	11.9	14.7
			3/4	21.0	21.5	17.1	21.2
		2	3/8	4.58	4.58	4.28	4.58
			1/2	8.14	8.14	7.60	8.14
			5/8	12.7	12.7	11.9	12.7
			3/4	18.3	18.3	17.1	18.3
		3	3/8	3.77	3.77	3.77	3.77
			1/2	6.70	6.70	6.70	6.70
			5/8	10.5	10.5	10.5	10.5
			3/4	15.1	15.1	15.1	15.1

Note:
Tabulated values are applicable only to concrete made with ASTM C33 aggregates for normal weight concrete and ASTM C330 aggregates for lightweight concrete.
After-weld steel headed stud anchor lengths assumed to be ≥ Deck height + 1.5 in.

Shear Stud Capacity

- Pre-calculated values in the table are most convenient
- No factor of safety or omega factor needs to be applied

F_u = 65 ksi

Table 3-21
Shear Stud Anchor

Q_n

Nominal Horizontal Shear Strength for One Steel Headed Stud Anchor, Q_n, kips

Deck condition		Stud anchor diameter, in.	Normal weight concrete w_c = 145 pcf		Lightweight concrete w_c = 110 pcf	
			f'_c = 3 ksi	f'_c = 4 ksi	f'_c = 3 ksi	f'_c = 4 ksi
No deck		3/8	5.26	5.38	4.28	5.31
		1/2	9.35	9.57	7.60	9.43
		5/8	14.6	15.0	11.9	14.7
		3/4	21.0	21.5	17.1	21.2
Deck Parallel	$\frac{w_r}{h_r} \geq 1.5$	3/8	5.26	5.38	4.28	5.31
		1/2	9.35	9.57	7.60	9.43
		5/8	14.6	15.0	11.9	14.7
		3/4	21.0	21.5	17.1	21.2
	$\frac{w_r}{h_r} < 1.5$	3/8	4.58	4.58	4.28	4.58
		1/2	8.14	8.14	7.60	8.14
		5/8	12.7	12.7	11.9	12.7
		3/4	18.3	18.3	17.1	18.3

F_u = 65 ksi

Table 3-21
Shear Stud Anchor

Q_n

Nominal Horizontal Shear Strength for One Steel Headed Stud Anchor, Q_n, kips

Deck condition			Stud anchor diameter, in.	Normal weight concrete w_c = 145 pcf		Lightweight concrete w_c = 110 pcf	
				f'_c = 3 ksi	f'_c = 4 ksi	f'_c = 3 ksi	f'_c = 4 ksi
Perpendicular	Weak studs per rib (R_p = 0.60)	1	3/8	4.31	4.31	4.28	4.31
			1/2	7.66	7.66	7.60	7.66
			5/8	12.0	12.0	11.9	12.0
			3/4	17.2	17.2	17.1	17.2
		2	3/8	3.66	3.66	3.66	3.66
			1/2	6.51	6.51	6.51	6.51
			5/8	10.2	10.2	10.2	10.2
			3/4	14.6	14.6	14.6	14.6
		3	3/8	3.02	3.02	3.02	3.02
			1/2	5.36	5.36	5.36	5.36
			5/8	8.38	8.38	8.38	8.38
			3/4	12.1	12.1	12.1	12.1
			3/8	5.26	5.38	4.28	5.31

Shear Connector Placement

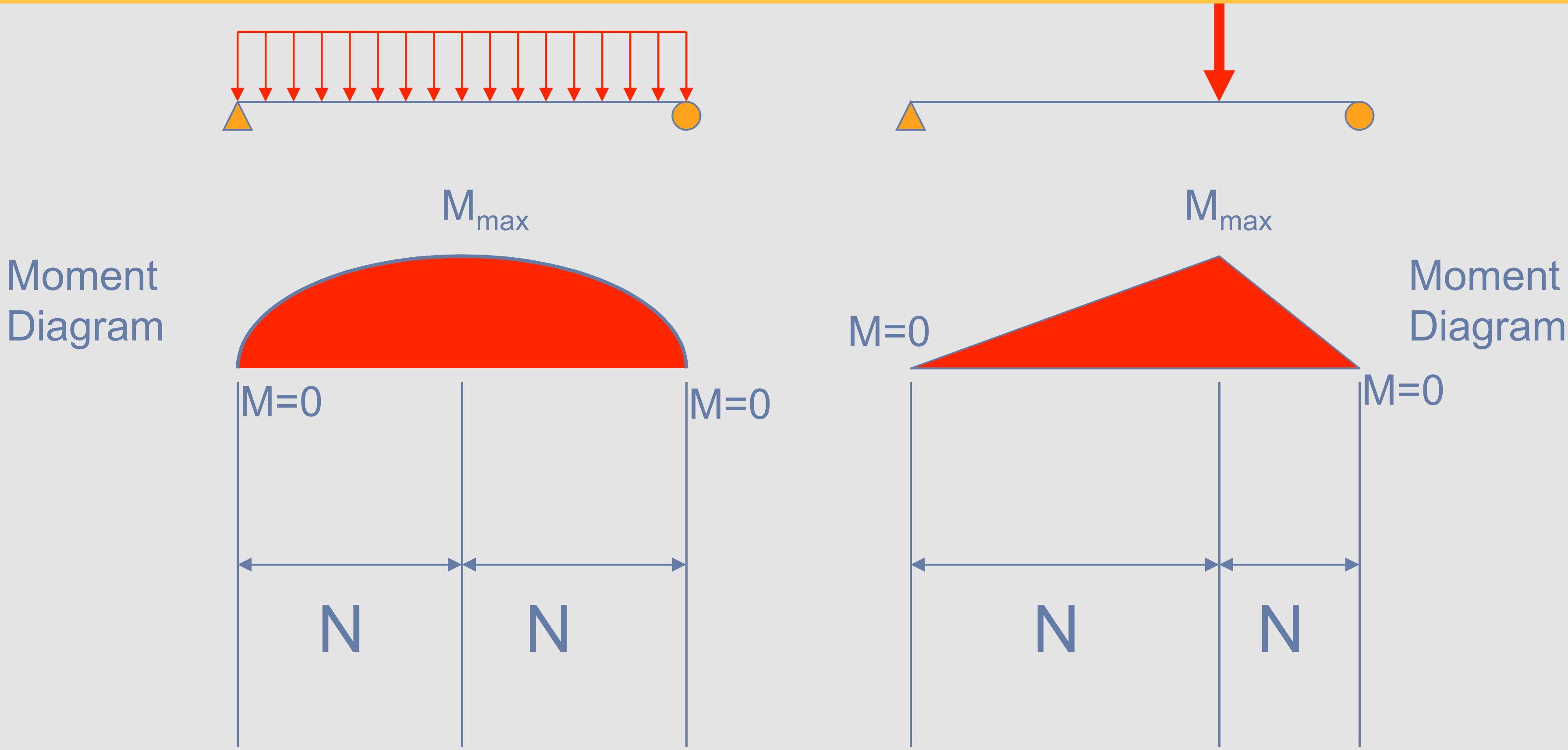
2c. Required Number of Steel Anchors

The number of anchors required between the section of maximum bending moment, positive or negative, and the adjacent section of zero moment shall be equal to the *horizontal shear* as determined in Sections I3.2d(1) and I3.2d(2) divided by the nominal shear strength of one *steel anchor* as determined from Section I8.2a or Section I8.2b. The number of steel anchors required between any concentrated *load* and the nearest point of zero moment shall be sufficient to develop the maximum moment required at the concentrated load point.

- **The total shear must be resisted on <u>each side</u> of the maximum moment!**

Spec I8.2c

Shear Connector Placement



N = number of shear connectors each side the point of max moment

Shear Connector Spacing

2d. Detailing Requirements

Steel anchors required on each side of the point of maximum bending moment, positive or negative, shall be distributed uniformly between that point and the adjacent points of zero moment, unless specified otherwise on the contract documents.

Steel anchors shall have at least 1 in. (25 mm) of lateral concrete cover in the direction perpendicular to the shear force, except for anchors installed in the ribs of formed steel decks. The minimum distance from the center of an anchor to a free edge in the direction of the shear force shall be 8 in. (203 mm) if normal weight concrete is used and 10 in. (250 mm) if *lightweight concrete* is used. The provisions of ACI 318, Appendix D are permitted to be used in lieu of these values.

The minimum center-to-center spacing of steel headed stud anchors shall be six diameters along the longitudinal axis of the supporting composite *beam* and four diameters transverse to the longitudinal axis of the supporting composite beam, except that within the ribs of formed steel decks oriented perpendicular to the steel beam the minimum center-to-center spacing shall be four diameters in any direction. The maximum center-to-center spacing of steel anchors shall not exceed eight times the total slab thickness or 36 in. (900 mm).

Spec I8.2d

Shear Connector Spacing

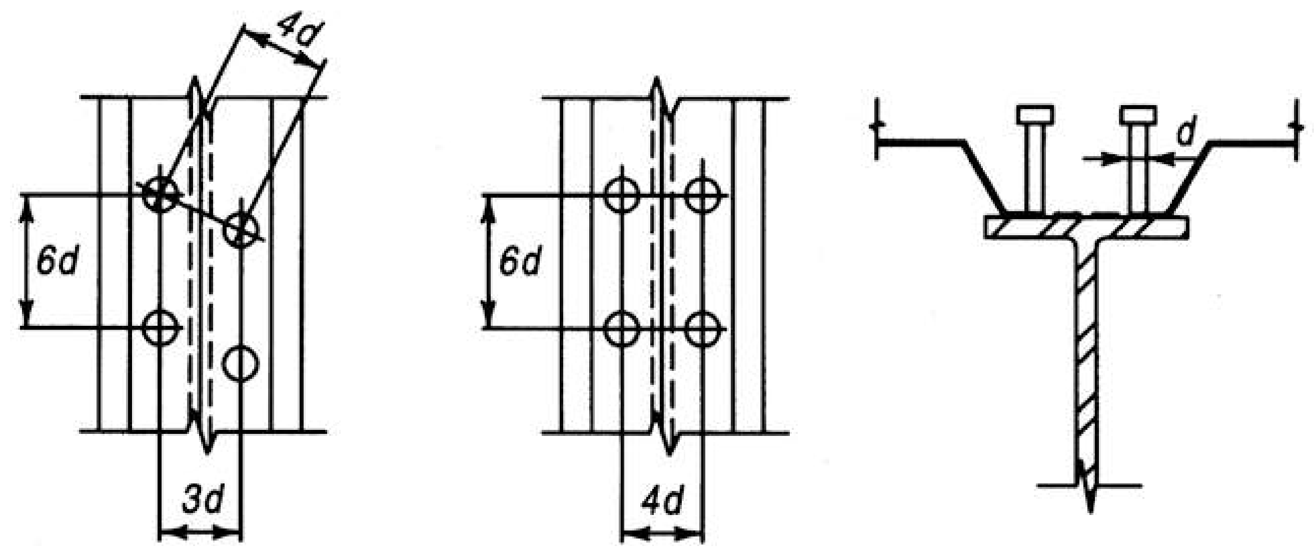
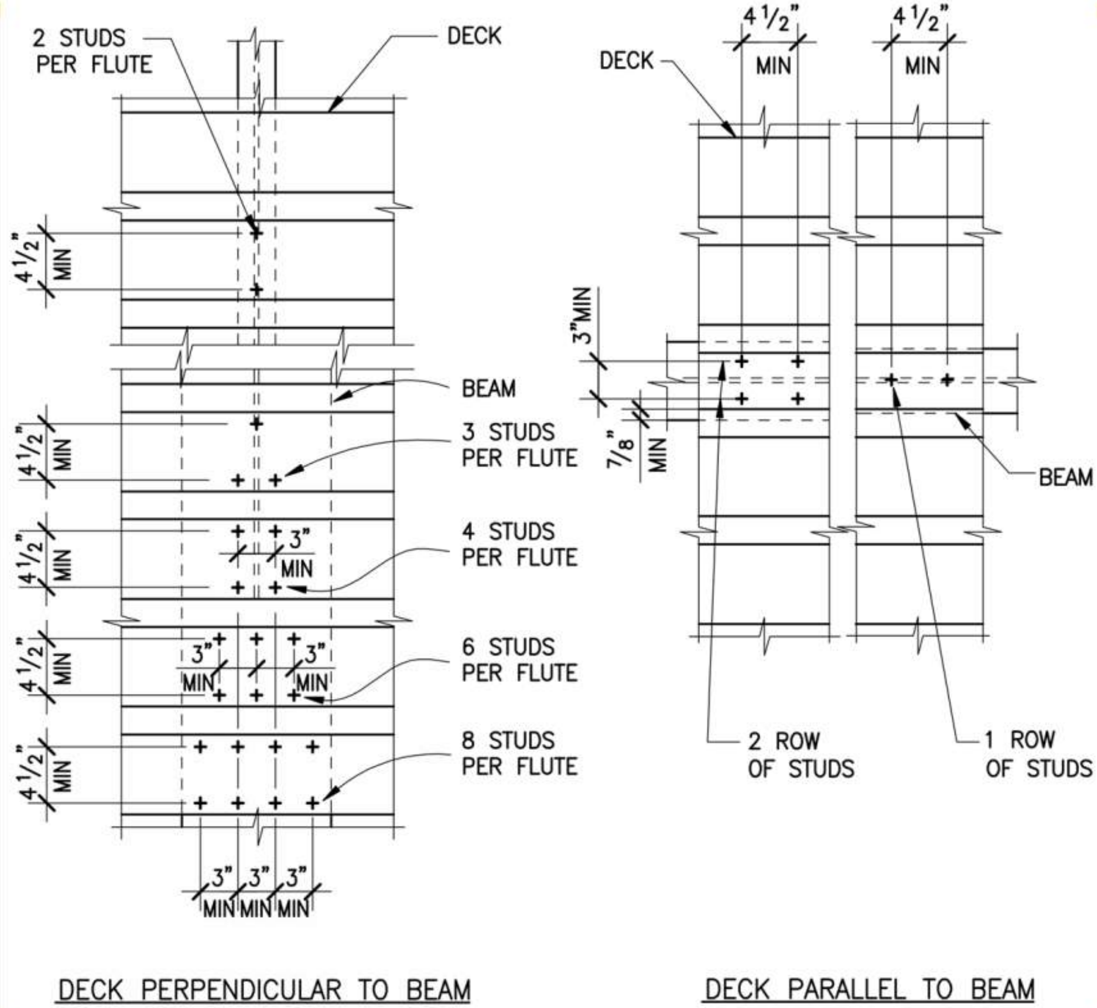


Fig. C-I8.3. Steel anchor arrangements.

- Min. Spacing = 6d
- Max Spacing = $8t_{slab}$
- Min Transverse Distance = 4d

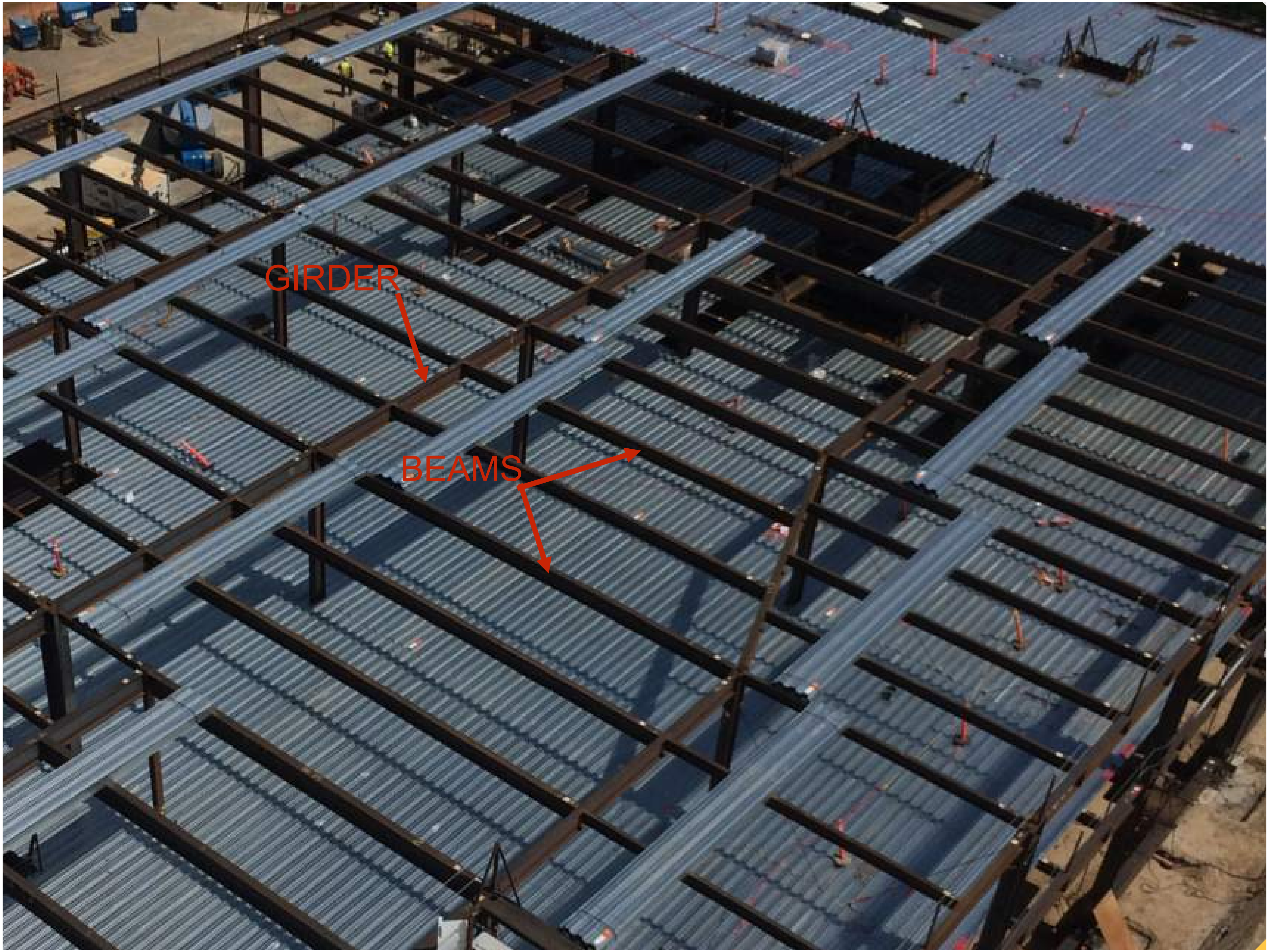
Spec C-I8.3

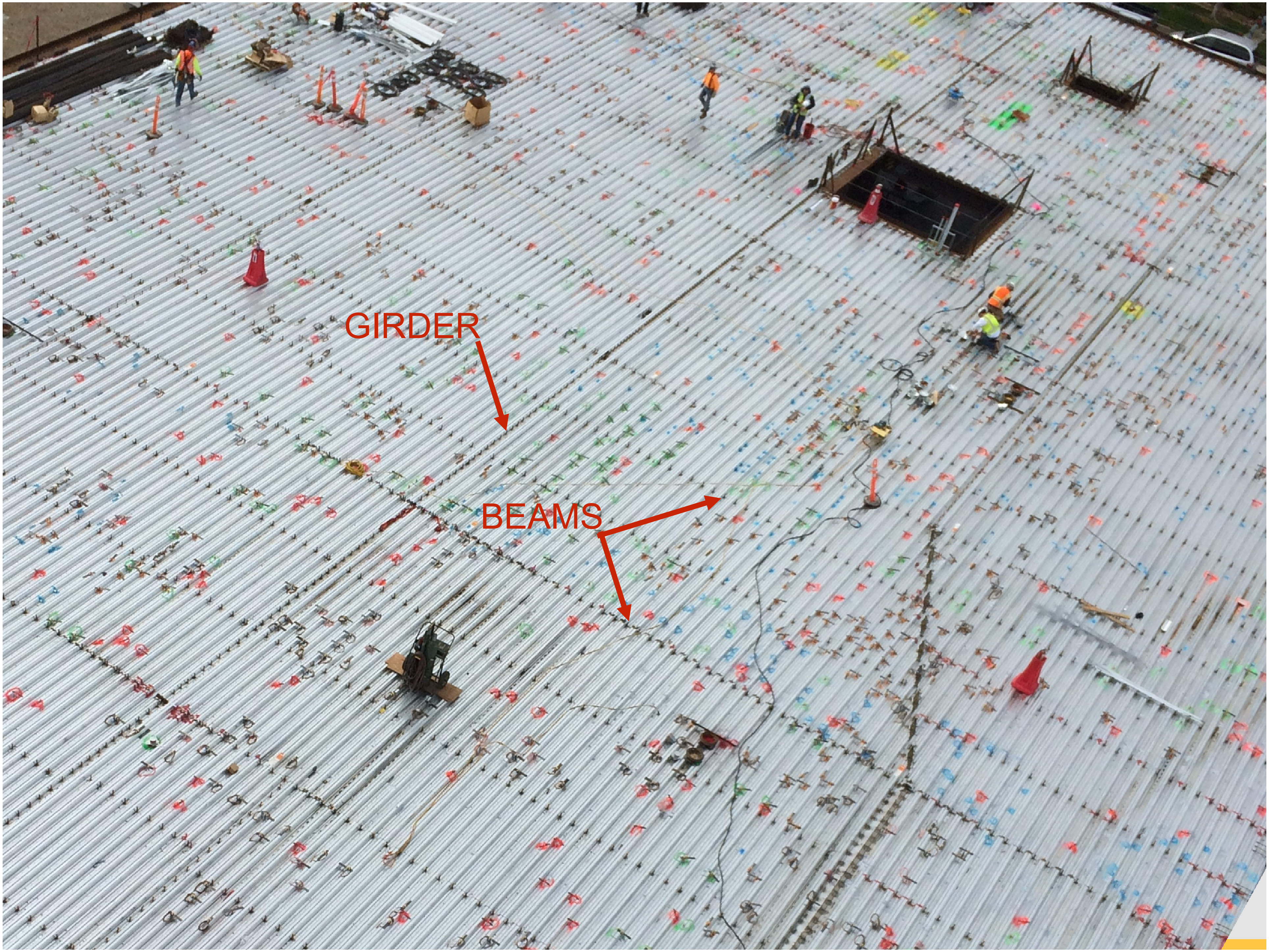
Shear Stud Position in Deck Flutes

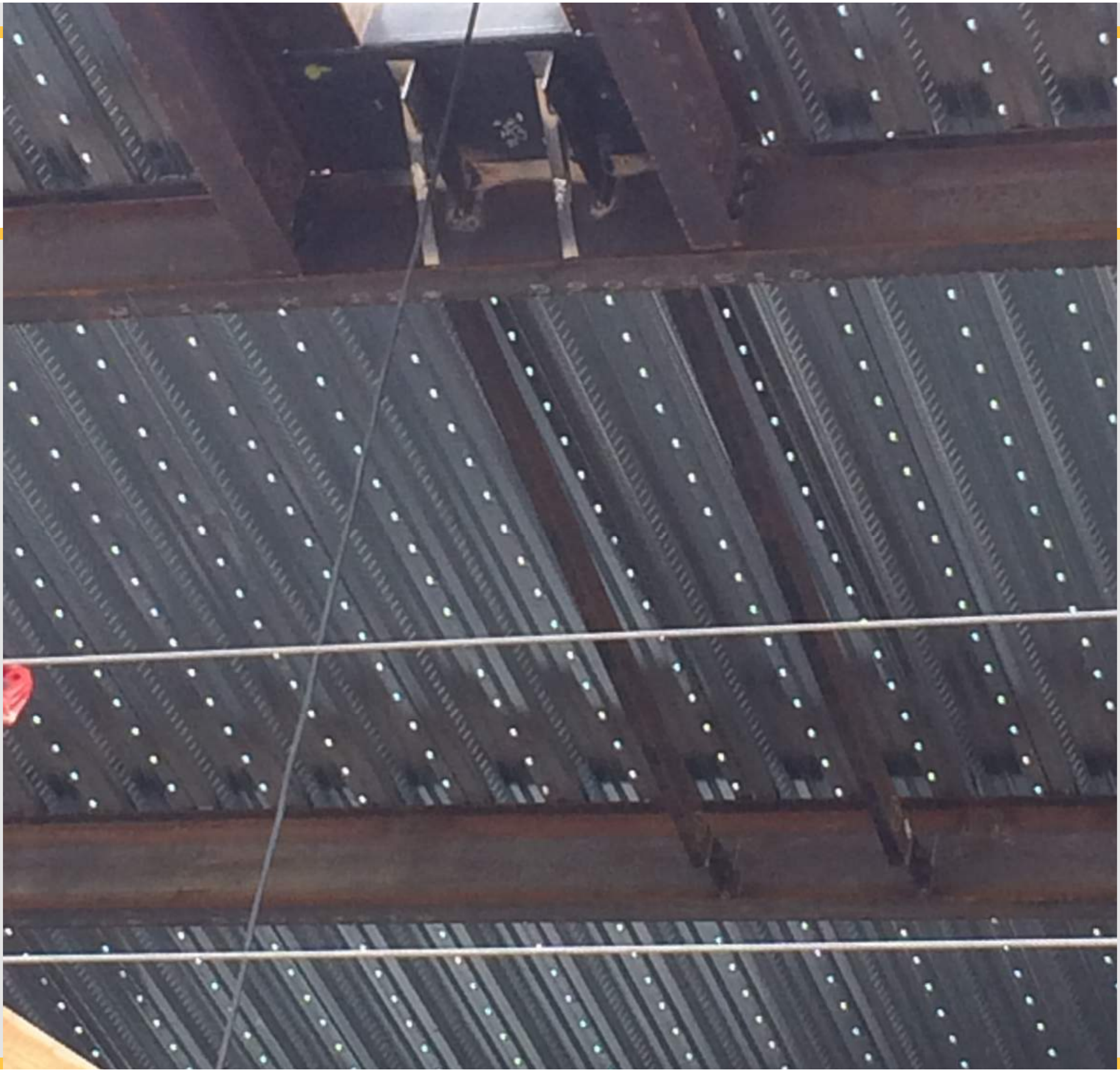


Construction Sequence

https://www.youtube.com/watch?v=SMJd3vSy6IY


GIRDER
BEAMS


GIRDER
BEAMS




(2) STUDS/RIB
(1) STUD/RIB


GIRDER W/ TIGHT
STUD SPACING


(1) STUD/RIB
(3) STUDS/RIB

Shear Flow Across the Concrete Slab/Steel Beam Interface

- Typically the first limit state a composite beam reaches is concrete crushing. Therefore, it is assumed that the both the steel beam and the concrete slab are plastic.
- The maximum shear flow which can occur across the interface is the minimum of the three limit states
  - Compression strength of concrete,
  - Tensile strength of steel beam,
  - Nominal strength of shear studs.

Three Limit States

(a) Concrete crushing

$$V' = 0.85 f_c' A_c \qquad \text{(I3-1a)}$$

(b) Tensile yielding of the steel section

$$V' = F_y A_s \qquad \text{(I3-1b)}$$

(c) Shear strength of steel headed stud or steel channel anchors

$$V' = \Sigma Q_n \qquad \text{(I3-1c)}$$

where

A_c = area of concrete slab within *effective width*, in.^{2} (mm^2)

A_s = area of steel cross section, in.^{2} (mm^2)

ΣQ_n = sum of *nominal shear strengths* of steel headed stud or steel channel anchors between the point of maximum positive moment and the point of zero moment, kips (N)

Fully vs Partially Composite

- Fully Composite
  - Enough shear stud anchors are provided to develop 100% of the capacity of the composite section
- Partially Composite
  - Enough shear stud anchors are provided to provide the capacity needed but not 100% of the composite section capacity based on concrete or steel strength
  - Should never be less than 25% of the fully composite capacity
- Headed studs typically provided at 12” o.c. Min

Questions